

ε'/ε COMPUTATION – LONG-DISTANCE EVOLUTION¹

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Abstract

We present a status report on our study of long-distance contributions to the decay amplitudes $A(K^0 \rightarrow 2\pi, I)$ in the framework of the $1/N$ expansion. We argue that a modified prescription for the identification of meson momenta in the chiral loop corrections has to be used to gain a self-consistent picture which allows an appropriate matching with the short-distance part. Possible uncertainties in the analysis of the density-density operators Q_6 and Q_8 which dominate the CP violation parameter ε'/ε are discussed. As a first result we present the long-distance $1/N$ correction to the gluon penguin operator Q_6 in the chiral limit.

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1 Introduction

The origin of CP asymmetries is an open issue within the electroweak theory. In the standard model CP violation arises from a complex phase introduced by hand in the Yukawa couplings. It is of special interest to investigate whether in this approach the ratio ε'/ε , the measure of direct CP violation in $K \rightarrow \pi\pi$ decays, may be close to zero, therefore mimicking the superweak model of Wolfenstein [1].

At present the experimental evidence is inconclusive,

$$Re\left(\frac{\varepsilon'}{\varepsilon}\right) = \left\{ \begin{array}{ll} (23 \pm 3.6 \pm 5.4) \cdot 10^{-4} & \text{NA 31 [2]} \\ (7.4 \pm 5.2 \pm 2.9) \cdot 10^{-4} & \text{E 731 [3]} \end{array} \right. , \quad (1)$$

and the new experiments are awaited to provide more accurate data.

In the standard model the calculation of ε'/ε is based on the effective low-energy hamiltonian for $\Delta S = 1$ transitions [4],

$$\mathcal{H}_{eff}^{\Delta S=1} = \frac{G_F}{\sqrt{2}} \xi_u \sum_{i=1}^8 c_i(\mu) Q_i(\mu) , \quad (2)$$

$$c_i(\mu) = z_i(\mu) + \tau y_i(\mu) , \quad \tau = -\xi_t/\xi_u , \quad \xi_q = V_{qs}^* V_{qd} , \quad (3)$$

where the Wilson coefficient functions $c_i(\mu)$ of the local four-fermion operators $Q_i(\mu)$ are obtained by means of the renormalization group equation. They were computed in a comprehensive next-to-leading order analysis by two groups [5, 6]. Using eq. (2) the ratio ε'/ε reads

$$\frac{\varepsilon'}{\varepsilon} = \frac{G_F}{2} \frac{\omega}{|\varepsilon| |A_0|} Im \xi_t \sum_{i=1}^8 y_i \left(\langle Q_i \rangle_0 - \frac{1}{\omega} \langle Q_i \rangle_2 \right) , \quad \omega^{-1} = \frac{Re A_0}{Re A_2} \simeq 22 . \quad (4)$$

$\langle Q_i \rangle_I$ are the hadronic matrix elements for the isospin states I which contain the long-distance contribution to the amplitudes A_I for the process under consideration,

$$\langle Q_i(\mu) \rangle_I \equiv \langle \pi\pi, I | Q_i(\mu) | K^0 \rangle . \quad (5)$$

The dominant CP violating effects result from the gluon and the electroweak penguins, $\langle Q_6 \rangle_0$ and $\langle Q_8 \rangle_2$ respectively, with

$$Q_6 = -2 \sum_{q=u,d,s} \bar{s}(1 + \gamma_5) q \bar{q}(1 - \gamma_5) d , \quad Q_8 = -3 \sum_{q=u,d,s} e_q \bar{s}(1 + \gamma_5) q \bar{q}(1 - \gamma_5) d , \quad (6)$$

where $\langle Q_6 \rangle_2$ in addition arises through isospin breaking effects ($\pi\eta\eta'$ mixing). Consequently, the main task within the investigation of long-distance effects is to estimate the degree of cancellation between the two penguin contributions in eq. (4) which gives rise to a small value of the ratio ε'/ε .

Although recently there has been considerable progress in lattice calculations of the hadronic matrix elements [7], it is still meaningful to improve the existing phenomenological studies in order to see whether the results are in agreement. There are several

approximations of non-perturbative QCD available [8, 9, 10]. We shall perform our analysis applying the $1/N$ expansion (N being the number of colors) where we will point out that a consistent matching between short- and long-distance contributions is possible, provided a proper identification of meson momenta in the chiral loop corrections is carried out.

2 General Framework: $1/N$ Expansion

To estimate the hadronic matrix elements we shall use the chiral effective lagrangian for $K \rightarrow \pi\pi$ decays, which involves an expansion in meson momenta where terms up to $\mathcal{O}(p^2/\Lambda_\chi^2)$ are included, Λ_χ being the chiral symmetry breaking scale of $\mathcal{O}(1\text{GeV})$ [8],

$$\mathcal{L}_{eff} = \frac{f^2}{8} \text{Tr} \left(D_\mu U D^\mu U^\dagger + r(mU^\dagger + Um^\dagger) \right) - \frac{f^2 r}{8\Lambda_\chi^2} \text{Tr} \left(m D^2 U^\dagger + D^2 U m^\dagger \right). \quad (7)$$

f and r are free parameters related to the pion decay constant F_π and to the quark masses, respectively, $m = \text{diag}(m_u, m_d, m_s)$ being the quark mass matrix. The degrees of freedom of the complex matrix U are identified with the pseudoscalar meson nonet, given in a non-linear representation,

$$U = \exp \frac{2i}{f} \pi^a \lambda_a = \exp \frac{i\sqrt{2}}{f} \begin{bmatrix} \pi^0 + \frac{\eta_8}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta_0 & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{\eta_8}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta_0 & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2\eta_8}{\sqrt{3}} + \sqrt{\frac{2}{3}}\eta_0 \end{bmatrix}. \quad (8)$$

A straightforward bosonization yields the chiral representation of the corresponding quark currents and densities, which allows to express the four-fermion operators Q_i in terms of the meson fields,

$$\begin{aligned} (J_L^\mu)_{ij} &\equiv \bar{q}_i \gamma^\mu (1 - \gamma_5) q_j = \frac{if^2}{4} \left(2\partial^\mu U U^\dagger - \frac{r}{\Lambda_\chi^2} (m\partial^\mu U^\dagger - \partial^\mu U m^\dagger) \right)_{ji}, \\ (D_L)_{ij} &\equiv \bar{q}_i (1 - \gamma_5) q_j = -\frac{f^2}{4} r \left(U - \frac{1}{\Lambda_\chi^2} \partial^2 U \right)_{ji}. \end{aligned} \quad (9)$$

The $1/N$ corrections to the matrix elements $\langle Q_i \rangle_I$ are calculated by chiral loop diagrams. In these diagrams we encounter divergences which are regularized by a finite cutoff Λ_{cut} as it was introduced by Bardeen, Buras and Gérard (BBG) to estimate the long-distance contribution to the $\Delta I = 1/2$ rule [8].

The inclusion of the one-loop corrections leads to a quadratic as well as to a logarithmic dependence of the matrix elements on the cutoff, i.e., the results are given in terms of

$$\sim \frac{\Lambda_{cut}^2}{(4\pi f)^2}, \quad \sim \frac{m_A^2}{(4\pi f)^2} \ln \left(1 + \frac{\Lambda_{cut}^2}{m_B^2} \right) \quad (10)$$

($m_{A,B}$ being pseudoscalar meson masses), where the quadratic part corresponds to the chiral limit ($m_q = 0$). Actually, the loop expansion involves a series in $1/f^2 \sim 1/N$, which is in direct accordance to the short-distance expansion in $\alpha_s/\pi \sim 1/N$.

Due to the truncation to pseudoscalar mesons, Λ_{cut} has to be taken at or even below the $\mathcal{O}(1\text{GeV})$. This restriction is a common feature of the phenomenological approaches at hand, in which higher resonances are not included.

To retain the physical amplitudes A_I , which as a matter of principle are scale-independent, the long- *and* the short-distance contributions are evaluated at the cutoff scale, i.e., the long-distance ultraviolet cutoff is identified with the short-distance infrared one. This procedure for the matching of the Wilson coefficient functions with the hadronic matrix elements we shall analyse in detail in the following section.

3 Chiral Loop Corrections

As mentioned above the calculation of chiral loop effects motivated by the $1/N$ expansion was introduced by BBG to explain the $\Delta I = 1/2$ rule. The authors considered the loop corrections to the current-current operators Q_1 and Q_2 , whereas the gluon penguin operator Q_6 was included at the tree level [8], implicitly assuming that the $1/N$ corrections to the latter are small.

Following the same lines Buchalla *et al.* [11] performed a detailed analysis of the ratio ε'/ε , in which they stressed that through the quadratic dependence of $\langle Q_6 \rangle$ and $\langle Q_8 \rangle$ on the running mass m_s the evolution of the corresponding Wilson-coefficients is cancelled in the large- N limit without considering chiral loops. One crucial result of their investigations is a small value of ε'/ε , caused by a large cancellation between the gluon and the electroweak penguin contributions.

Heinrich *et al.* extended the analysis by including chiral loops, i.e., the $1/N$ corrections to the matrix elements of Q_6 and Q_8 [12, 13]. As a net effect they reported an enhancement of $\langle Q_6 \rangle_0$ and a large decrease for $\langle Q_8 \rangle_2$, through which the cancellation gets less effective. Numerically the authors found a large positive value of ε'/ε [14],

$$\varepsilon'/\varepsilon = (9.9 \pm 4.1) \cdot 10^{-4} \quad [m_s(1\text{GeV}) = 175\text{ MeV}] . \quad (11)$$

The relative size of the $1/N$ corrections contained in eq. (11) has to be compared with the factors B_6 and B_8 , denoting deviations from the lowest order results for the corresponding matrix elements, as obtained e.g. by lattice calculations. The latter give [7]

$$B_6^{(I=0)} = 1.0 \pm 0.2 \quad \text{and} \quad B_8^{(I=2)} = 1.0 \pm 0.2 \quad (12)$$

(in accordance with a recent QCD sum rule analysis of $\langle Q_6 \rangle$ [9]), predicting again a strong cancellation between the various penguin contributions. In view of this different results we perform a detailed reconsideration of chiral loop effects in the $1/N$ approach.

One crucial point within our analysis of the $K \rightarrow \pi\pi$ decay amplitudes is the matching of short- and long-distance contributions at the cutoff scale. In the *standard approach* referred to above, the effective color singlet gauge boson connecting the two currents and densities, respectively, is integrated out from the beginning. The basic diagrams hence to be

calculated are presented in fig. 1 where the squares denote weak vertices corresponding to the bosonized four-fermion operators Q_i and the circles indicate strong interaction vertices.

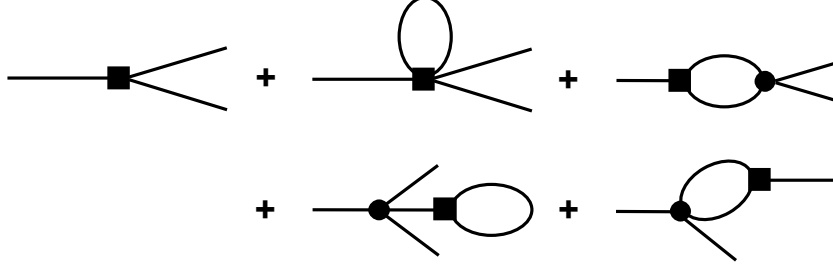


Fig. 1: Chiral diagrams for $K \rightarrow \pi\pi$ decays.

Within this procedure the cutoff Λ_{cut} is associated to the meson in the loop, i.e., the integration variable is identified with the meson momentum. Consequently, as there is no corresponding quantity in the short-distance part, *a rigorous matching of long- and short-distance contributions is not possible*.

The ambiguity is removed by associating the cutoff to the effective color singlet gauge boson as introduced within a study of the K_L - K_S mass difference [15] and recently used by Fatelo and Gérard who calculated the long-distance evolution of **current-current operators** in the chiral limit applying the $1/N$ expansion [16]. The corresponding identification of the loop integration variable with the momentum flow between the two currents and densities, respectively, is feasible in the long- *and* the short-distance part of the analysis, through which a direct momentum matching is justified.

The crucial feature of this *modified approach* is illustrated in fig. 2. The momentum of the virtual meson is shifted by the external momentum, the former being no longer identical to the integration variable q , which affects both, the quadratic and the logarithmic behaviour of the $1/N$ corrections.

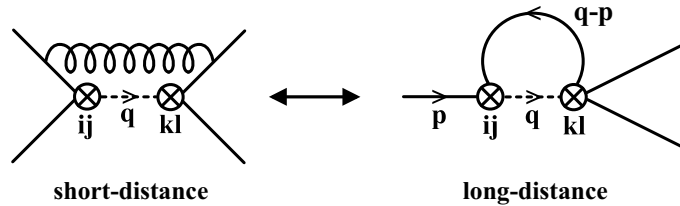


Fig. 2: Matching of short- and long-distance contributions.

Obviously the modified procedure described above is applicable only for the *non-factorizable* part of the interaction. In fig. 3 we split the first loop diagram of fig. 1 respecting the mesonic currents which contribute to the matrix element $\langle \pi^+ \pi^- | Q_2 | K^0 \rangle$, where $Q_2 \equiv (J_\mu^L)_{su} (J_\mu^L)_{ud}$.

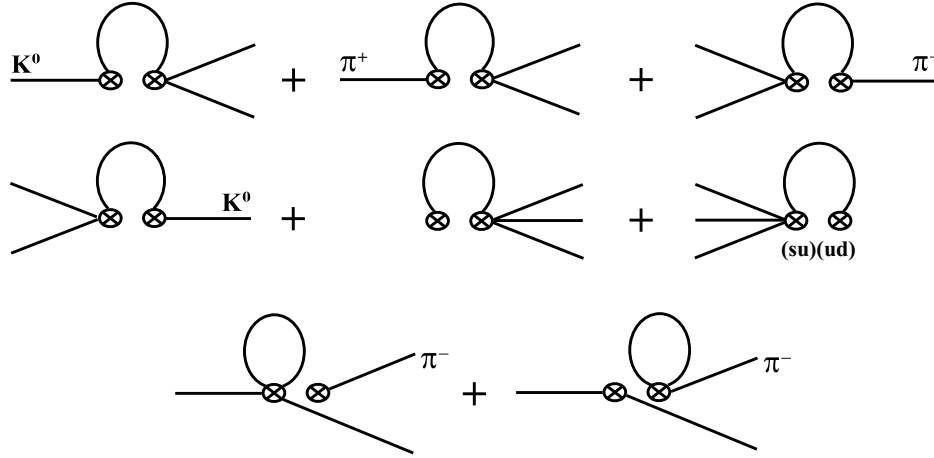


Fig. 3: Representative loop contribution to the matrix element $\langle \pi^+ \pi^- | Q_2 | K^0 \rangle$, the cross circles denoting the currents $(J_\mu^L)_{su}$ (left circle) and $(J_\mu^L)_{ud}$ (right) for incoming particles.

The *factorizable* loop corrections shown in the third row are completely absorbed through the renormalization of the mesonic wave function and the bare decay constant f , a pure long-distance feature connected with current conservation and the knowledge of the physical decay constant F_π .

Calculating all diagrams of fig. 1, splitted according to a clear identification of the virtual meson momenta, the evolution of the matrix element in the chiral limit reads

$$\langle \pi^+ \pi^- | Q_2(\Lambda_{cut}) | K^0 \rangle = F_\pi(m_K^2 - m_\pi^2) \left[1 + 3 \frac{\Lambda_{cut}^2}{(4\pi)^2} \frac{1}{f^2} + \mathcal{O}(1/N^2) \right], \quad (13)$$

the factor of 3 in front of the cutoff dependent term to be compared with a factor of 2 obtained in ref. [8]. The result presented in eq. (13) is identical to the one derived from a study of the operator evolution [16], where the analysis of the matrix element allows us to include in addition the logarithmic cutoff dependence arising through non-vanishing quark masses (currently being under investigation).

As illustrated above a rigorous analysis of current-current hadronic operators using the modified $1/N$ approach is feasible. The treatment of **density-density operators**, Q_6 and Q_8 being dominant for ε'/ε , requires additional remarks.

Whereas the *factorizable* part of the loop diagrams can be removed in the case of current-current operators, the corresponding contributions have to be considered explicitly for density-density operators; a feature due to the absence of a conservation law for densities and, in addition, to the ignorance of a low-energy constant, analogous to the decay constant F_π in case of the currents, in which the loop corrections could be absorbed.

Since a clear identification of the virtual meson momenta from a comparison with the short-distance part is not at hand for factorizable diagrams (representing pure long-distance phenomena), there is no prescription to fix a possible shift ($q \rightarrow q + p$). Consequently, an *ambiguity in the sub-leading divergent terms* occurs.

On account of chiral symmetry no quartic dependence on the cutoff is present in the matrix elements. Nevertheless, single loop diagrams may produce quartic terms which cancel in the sum. Thus a dependence on the (arbitrary) momentum shift may result in the $\mathcal{O}(\Lambda_{cut}^2)$. A concrete analysis however shows that in case of the density-density operators each factorizable diagram is at most quadratically divergent, the ambiguity only arising in the logarithmic terms. This characteristic is based on the symmetric structure of the meson density given in eq. (9), through which the weak vertex solely involves the *sum* of the two (incoming) virtual momenta q_1 and q_2 ,

$$(D_L)_{ij} \rightarrow (\partial^2 U)_{ji} \rightarrow (\partial^2 [\pi^a \lambda_a]^n)_{ji} \rightarrow (q_1 + q_2 + \dots)^2 = p_{ext}^2, \quad (14)$$

$q_1 + q_2$ being independent of the integration variable q (n denoting the number of particles, p_{ext} the external momentum associated with the density).

A strict analysis of the *non-factorizable* contributions can be performed for density-density in the same way as for current-current operators. Consequently, from the sum of the factorizable and the non-factorizable parts we can clearly determine the quadratic cutoff dependence of the matrix elements.

Splitting the basic diagrams of fig. 1 for the gluon penguin operator $Q_6 = -2(D_R D_L)_{sd}$ we may calculate the evolution of the corresponding matrix elements for $K \rightarrow \pi\pi$ decays. The final result (obtained from about 100 explicit diagrams) reads

$$\langle \pi^+ \pi^- | Q_6 | K^0 \rangle = \langle \pi^0 \pi^0 | Q_6 | K^0 \rangle = -F_\pi (m_K^2 - m_\pi^2) \frac{r^2}{\Lambda_\chi^2} \left[1 + 3 \frac{\Lambda_{cut}^2}{(4\pi)^2 f^2} + \mathcal{O}(1/N^2) \right], \quad (15)$$

where

$$F_\pi = f \left[1 - 3 \frac{\Lambda_{cut}^2}{(4\pi f)^2} \right], \quad r^2 = \frac{(2m_K^2 - m_\pi^2)^2}{m_s^2 (\Lambda_{cut})}. \quad (16)$$

Note that (due to the inclusion of the η_0) the parameter r^2 has no quadratic cutoff dependence.

It is known that the value of the chiral symmetry breaking parameter Λ_χ increases through logarithmic corrections from $\Lambda_\chi(\text{LO}) \simeq 1.02 \text{ GeV}$ to $\Lambda_\chi(\text{NLO}) \simeq 1.20 \text{ GeV}$ (see BBG [8]), thus counteracting the increase caused by the explicit loop contributions given in eq. (15). Consequently, we expect the $1/N$ corrections to the matrix element of Q_6 to be small.

To perform however a detailed numerical analysis in view of the ratio ε'/ε , we have to include in addition the logarithmic terms which arise from the *explicit* loop corrections. These terms can be calculated in a straightforward way only for the non-factorizable diagrams. To determine the logarithmic behaviour in the factorizable part one has to introduce a clear prescription to fix the virtual meson momenta. As we have seen this is not possible from a direct matching with the short-distance contributions. This issue is still to be investigated.

4 Operator Evolution

To gain a deeper understanding of long-distance effects we may study the $1/N$ corrections to density-density operators themselves rather than those to the matrix elements. For that we may apply the **background field method** as used by Fatelo and Gérard in the case of current-current operators [16]. This approach is powerful as

- the one-loop effects are given in terms of operators, too. Therefore the analysis is *process independent* (respecting the various decay channels of $K \rightarrow \pi\pi$).
- the calculation keeps track of the *chiral structure* in the loop corrections.

Whereas the method is particularly powerful in the chiral limit on account of the (relatively) small number of diagrams which have to be calculated, the inclusion of mass terms is difficult, wherefore we restrict our analysis to the case of massless quarks, i.e., to the quadratic cutoff dependence.

Starting from the chiral limit ($m_q = 0$), in the lagrangian we have to keep a mass term for the singlet pseudoscalar η_0 arising through the explicit breaking of the $U_A(1)$ symmetry,

$$\begin{aligned}\mathcal{L} &= \frac{f^2}{8} \left(\text{Tr}(\partial_\mu U \partial^\mu U^\dagger) + \frac{m_0^2}{12} [\text{Tr}(\ln U - \ln U^\dagger)]^2 \right) \\ &= \bar{\mathcal{L}} + \frac{1}{2} (\partial_\mu \xi^a \partial^\mu \xi^a) + \frac{1}{2} \text{Tr}([\partial_\mu \xi, \xi] \partial^\mu \bar{U} \bar{U}^\dagger) - \frac{1}{2} m_0^2 \xi^0 \xi^0 + \mathcal{O}(\xi^3) .\end{aligned}\quad (17)$$

To obtain the second line of eq. (17) we decomposed the matrix U in the quantum field ξ and the classical field \bar{U} ,

$$U = \exp(2i\xi/f) \bar{U} , \quad \xi = \lambda_a \xi^a , \quad (18)$$

\bar{U} satisfying the equation of motion

$$\bar{U} \partial^2 \bar{U}^\dagger - \partial^2 \bar{U} \bar{U}^\dagger = \frac{m_0^2}{N} \text{Tr}(\ln \bar{U} - \ln \bar{U}^\dagger) \cdot 1 , \quad \bar{U} = \exp(2i\pi^a \lambda_a / f) . \quad (19)$$

If in the same way we expand the meson density, given in eq. (9), around the classical field (with $U \leftrightarrow U^\dagger$ for $L \leftrightarrow R$), which yields

$$\begin{aligned}(D_R)_{ij} &= (\bar{D}_R)_{ij} + \frac{if}{2} \left(\bar{U}^\dagger \xi - \frac{1}{\Lambda_\chi^2} (\partial^2 \bar{U}^\dagger \xi + 2\partial_\mu \bar{U}^\dagger \partial^\mu \xi + \bar{U}^\dagger \partial^2 \xi) \right)_{ji} + \frac{r}{2} [\bar{U}^\dagger \xi^2 \\ &\quad - \frac{1}{\Lambda_\chi^2} (\partial^2 \bar{U}^\dagger \xi^2 + 2\partial_\mu \bar{U}^\dagger \{\partial^\mu \xi, \xi\} + \bar{U}^\dagger (\{\partial^2 \xi, \xi\} + 2\partial_\mu \xi \partial^\mu \xi))]_{ji} + \mathcal{O}(\xi^3) ,\end{aligned}\quad (20)$$

we may calculate the $1/N$ correction to a density-density operator of the form $(D_R)_{ij}(D_L)_{kl}$ by integrating out the ξ field, the terms linear in ξ in eq. (20) contributing to the *non-factorizable* one-loop diagrams, the quadratic to the *factorizable* ones, where the rescattering of the mesons due to the strong interaction may be included using the lagrangian

(17). The external legs of a diagram (see fig. 4) now symbolize weak and strong operators, respectively, given in terms of the field \bar{U} . Consequently, the loop corrections preserve the chiral structure.

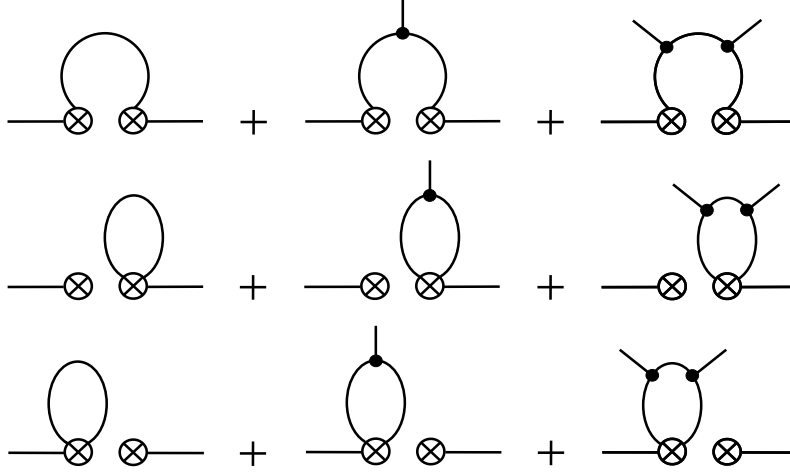


Fig. 4: One-loop $\mathcal{O}(p^2)$ contribution to the long-distance evolution of the operator $(D_R)_{ij}(D_L)_{kl}$, the cross circles denoting the densities, the black circles the strong interaction.

The *non-factorizable* part (first row of fig. 4) may again be calculated in a straightforward (although lengthy) way associating the cutoff to the effective color singlet gauge boson connecting the two densities. The *factorizable* contributions however (second and third row of fig. 4), involving trilinear divergences through a certain class of diagrams, show a dependence on a shift of the loop momenta ($q \rightarrow q + p$) already in the quadratic cutoff behaviour. This feature, occurring in the study of the operator evolution by means of the background field approach, does not appear in the explicit analysis of the various matrix elements (see section 3).

In order to avoid an ambiguity of the operator evolution in the chiral limit, it is sufficient to adopt a prescription for the *distribution* of momenta in the concerned diagrams. Indeed we have strong indications for a particular choice (based on arguments beyond the scope of this talk), which removes any further shift dependence from the quadratic terms. This choice is natural but not necessarily unique.

Thus performing the analysis, from the sum of the factorizable and the non-factorizable parts we obtain the long-distance evolution of the operator Q_6 ,

$$Q_6(\Lambda_{cut}^2) = -\frac{F_\pi^4}{4} \frac{r^2}{\Lambda_\chi^2} (\partial_\mu \bar{U} \partial^\mu \bar{U}^\dagger)_{ds}(0) \left[1 + 3 \frac{\Lambda_{cut}^2}{(4\pi f)^2} + \mathcal{O}(1/N^2) \right], \quad (21)$$

the chiral loop corrections being identical to those found in the study of the matrix element (using the background field approach the renormalization factors for the bare decay constant f and the bare meson field π^a cancel in the matrix \bar{U}).

Note that the result is given in terms of $(\partial_\mu \bar{U} \partial^\mu \bar{U}^\dagger)_{ds}$, the latter being the only pseudoscalar operator available at the $\mathcal{O}(p^2)$ to describe both, the corresponding current-current and density-density four-fermion operators (Q_4 and Q_6 , respectively).

5 Summary and Conclusion

We studied the one-loop long-distance contributions to $K \rightarrow \pi\pi$ decay amplitudes applying the $1/N$ expansion in which we used the momentum flow between the currents and densities, respectively, to fix the virtual meson momenta. Thus a proper matching with the short-distance part is feasible for non-factorizable diagrams.

The matrix elements of density-density operators, containing factorizable contributions which have to be considered explicitly, were found to be clearly determined regarding the quadratic cutoff behaviour, yet leaving us with an ambiguity in the logarithmic one. In the evolution of the operators themselves, which we investigated by means of the background field approach, the corresponding ambiguity already appeared in the quadratic divergences. However, using a prescription motivated by theoretical arguments the methods are in agreement.

As a first analytic result we presented the $1/N$ corrections to the gluon penguin operator Q_6 as well as to the corresponding matrix elements in the chiral limit. The corrections are small, provided the change in the value of the hadronic scale Λ_χ is considered. A detailed numerical analysis in view of the ratio ε'/ε requires in addition the inclusion of logarithmically divergent terms. This issue is still under investigation.

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